# Enhanced operating flexibility and optimised off-design operation of coal plants with post-combustion capture

**Citation for published version:**
Lucquiaud, M, Fernandez, ES, Chalmers, H, Dowell, NM & Gibbins, J 2014, 'Enhanced operating flexibility and optimised off-design operation of coal plants with post-combustion capture', *Energy Procedia*, vol. 63, pp. 7494-7507. https://doi.org/10.1016/j.egypro.2014.11.786

**Digital Object Identifier (DOI):**
10.1016/j.egypro.2014.11.786



**Published In:**
Energy Procedia

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 63 (2014) 7494 – 7507

Energy Procedia

GHGT-12

# Enhanced operating flexibility and optimised off-design operation of coal plants with post-combustion capture

Mathieu Lucquiaud[a,*], Eva Sanchez Fernandez[a], Hannah Chalmers[a], Niall Mac Dowell[b], Jon Gibbins[a]

[a]*The University of Edinburgh, School of Engineering, The Kings Buildings, Edinburgh EH9 3JL, United Kingdom*
[b]*Centre for Environmental Policy, Imperial College London, United Kingdom*

**Abstract**

The inherent nature of electricity necessitates a permanent balance between generation and demand in electricity systems. This has obvious implications for the operation of CCS power plants in decarbonised electricity systems with inflexible nuclear and variable renewable supply. The low variable costs of nuclear and some intermittent renewable technology allow them to run as base-load generators and shift fossil fuel plants from base-load to mid-merit plants. CCS power plants can be expected to increasingly operate in ways to balance variations, sometimes simultaneously, in the production of some intermittent renewable technologies and variations in electricity demand, resulting in more frequent ramping and start/stop cycles. As a result, they may also operate over a wide output range to maintain the quality and security of electricity supply by providing ancillary services, e.g. capacity and energy reserve, to the electricity network. This work characterises the operating envelope, the performance and the corresponding compressed $CO_2$ flow of coal power plants for a range of loads, with or without voluntary by-pass of the capture unit. Optimised part-load operating strategies provide novel insights into the additional capabilities of CCS power plants specifically designed for enhanced operating flexibility.


Peer-review under responsibility of the Organizing Committee of GHGT-12

*Keywords:* Integration ; Post-combustion carbon capture; flexibility; part-load

* Corresponding author. Tel.: +44-131-650-8697;
*E-mail address:* m.lucquiaud@ed.ac.uk


Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.786

## 1. Introduction

Flexible operation of the capture unit has been widely suggested as a way to improve the flexibility and the economics of CCS power plants. There is an increasing body of literature examining the value of that flexibility to the electricity system, with various studies highlighting that this can be associated with an increase in plant revenues when electricity prices are high and/or from balancing services [1 - 7]. This is, in effect, highly dependent on the differential in of electricity prices and the amount of wind generation in the electricity system considered. Brasington [8] showed that flexibility with amine solvent storage does not increase profitability under the set of electricity price spreads that were considered. Patino-Echeverri and Hoppock [9] then proposed specific metrics for determining if amine-storage can reduce CCS operating costs by taking advantage of arbitrage opportunities present in cyclical electricity price differentials. They showed that flexibility with amine storage may be marginally cost-effective for retrofitted plants in a few electricity markets with large price differentials.

On the other hand, Van der Wijk et al. [10] recently carried out a comprehensive study integrating an Excel model of a capture unit with an electricity system model of the North West part of Europe, including revenue from some ancillary services. Their model relies on minimising total system cost for future scenarios of carbon price and larger wind penetration in the Dutch electricity grid compared to current North American electricity markets. By comparing the revenues of different options for flexible CCS power plants to a non-flexible counterfactual they showed that the main benefit of flexible CCS is an increase in reserve capacity.

In addition to interacting with an increasingly complex electricity system, CCS power plants, beyond initial demonstration from a single source to a single $CO_2$ sink, will also have to operate within the constraints of a second network, namely the downstream $CO_2$ transport and storage system. The latter presents its own complexity due to constraints on $CO_2$ phase change, injection rates and gas composition. Although the nature of mechanisms that will be put in place with $CO_2$ transport network operators, i.e. the equivalent of the national/regional grid codes for electricity networks, fossil power plants with CCS will have to rise to these new challenges to achieve resilient integrated CCS systems.

For power plants fitted with post-combustion capture, the capacity to vary steam extraction levels from the power cycle to adjust both capture levels, possibly down to zero for some period of time, and power output is thus a valuable option to:

- maintain the output of the power plant in case of a failure either in the $CO_2$ capture, transport or storage part of the system,
- increase/decrease power output rapidly to meet grid code requirements,
- generate revenue in response to price signals in the electricity spot market,
- generate revenue in the reserve market

It is also possible that, as $CO_2$ generators in integrated CCS systems, this flexibility may become valuable to:

- maintain flow in a case of a failure in the transport system
- increase/decrease flows, possibly independently of electricity generation, to meet the requirements of transport networks
- generate revenue by adjusting compressed flow in response to signals for the transport network operator

## 2. Review of operating strategies of part-load operation

Dedicated operating strategies for part-load operation of the capture unit were proposed by Ziaii et al. [11], Ziaii [12] and Van der Wijk et al. [10]. They tend to examine the capture unit either in isolation of, or with limited interface with the power cycle and the compression train. For example, Ziaii et al [11] proposed a ratio-control dynamic strategy of the capture unit where the absorber operates continuously. A fraction of the rich solvent is recirculated from the outlet of the absorber to the inlet to by-pass the stripper, as the reboiler heat duty is either ramped up or down. Ziaii [12] proposed later a dedicated compressor control strategy for part-load integrated with a dynamic model of a capture unit. She concluded that for a specific $CO_2$ removal, there is a compressor speed and a solvent rate that minimizes total equivalent work, and that a variable speed compressor is advantageous for optimal operations. The conclusions from Ziaii [12] are based on the assumption that it is always possible to maintain the reboiler temperature at a constant temperature when the plant is operated at part-load.

Van der Wijk et al [10] considered two operating strategies for part load operation of capture plants. A constant ratio of gas and liquid in the absorber, whilst maintaining a constant capture rate, combined with a flexible plant configuration with one absorber column, two parallel stripper columns and three parallel compressor trains, based on Ziaii et al., [11]. The second strategy is constant solvent flow rate in combination with a capture unit layout consisting of one absorber column, one stripper column and one compressor train. Van der Wijk et al. concluded that the electricity output penalty is lower at part-load at constant liquid gas ratio. The reduction in power output is assumed to be inversely proportional to the steam supply to the stripper, with a conversion factor based on an average for a state-of-the-art power generation unit.

In these studies, the interface between the power cycle and the capture is not described (Van der Wijk et al.) or simplified (Ziaii) since the effect of part-load operation on the pressure available from the power cycle, and by extension the reboiler temperature, are not accounted for. In Van der Wijk, the interface between the capture unit and the compression train is equally simplified with the assumption that the load of the compression train is proportional to the $CO_2$ flow, and the effects of changes in the volumetric flow rate of $CO_2$ at part-load are not included.

## 3. Typical modes of flexible CCS operation

Plant configurations for flexible CCS in the public domain literature operation are:

- Capture by-pass, also referred to as venting which was initially proposedby Gibbins and Crane [13] and updated by Chalmers and Gibbins [1]. The power station returns to either the full, or significantly closer to, 100% of its Maximum Continuous Rating, i.e. the maximum net power output, by diverting steam extracted for solvent regeneration back to the LP turbine and by turning down/off the compression train, and possibly other ancillaries such as the solvent pumps and/or gas blowers
- Solvent storage followed by delayed solvent regeneration [1, 13] where the plant has the ability to reduce considerably the energy penalty for a set period of time, possibly returning to 100% of Maximum Continuous Rating (MCR), and regenerate rich solvent at a later moment in time. If delayed solvent regeneration occurs when the boiler firing load is reduced, there is spare capacity in the solvent regeneration and $CO_2$ compression system that can be exploited without necessitating additional investment. The minimum additional investment necessary includes intermediate solvent tanks and pumps. A utility may also consider oversizing the solvent regeneration part of the capture unit and the compression train for additional solvent regeneration
- Time-varying solvent regeneration: Mac Dowell and Shah uses dynamic, rate-based models of the capture unit [14,15] and propose the option of using the working solvent as means to provide flexibility to the power plant [16, 17]. This is achieved by allowing the $CO_2$ to accumulate in the working solvent during hours of peak electricity prices and regenerating the solvent more completely during off peak periods. Solvent is not stored separately to the capture plant, but is stored by changing the solvent loading via the parameterisation of the lean loading control variable.

Assumptions about the capabilities and the performance of the plant when operated at part-load, and when operated with delayed solvent storage, have a large influence on the outcome of flexibility studies. Van der Wijk et al [10] compared a flexible CCS power plant oversized for 125% of solvent regeneration at 100% fuel input with 90% capture to a flexible CCS power plant sized for 100% solvent regeneration at 100% fuel input with 90% capture. They showed that at average electricity price, carbon intensity of electricity generation and wind curtailment were similar for the oversized plant and the 'standard' flexible CCS power plant. They concluded that solvent storage could be a viable option independent of the carbon price if solvent can be regenerated during hours of low demand, when the plant generator operates regularly at part-load when it is displaced by wind generation.

On the other hand, Oates et al [6] concluded that solvent storage could be used for capital cost gain by undersizing the regenerator to smooth out compressed $CO_2$ flow throughout the day.

Using a multi-period design approach, Mac Dowell and Shah [16] observed that time varying solvent regeneration approach has the potential to generate electricity that has, on average, a lower carbon dioxide intensity and to be more profitable than the options of either exhaust gas venting (or capture bypass) or solvent storage.

Further work is needed to understand the full implications of important parameters such as plant size, electricity system, revenue from $CO_2$ sales, capture level and understand to what extent these conclusions are sensitive to these parameters.

The model developed for this study characterises the operating envelope, the performance and the corresponding $CO_2$ output of coal power plants for a range of loads, varying from 40 to 100%, Maximum Continuous Rating, with or without voluntary by-pass of the capture unit, and a range of solvent regeneration rates. Optimised part-load operating strategies are proposed to improve performance at reduced fuel input and feed into studies on the economic assessment of power plant flexibility, and also into the growing field of integrated $CO_2$ networks.

Novel insights into the additional capabilities of CCS power plants specifically designed for enhanced operating flexibility are developed by taking into account the integration of the capture unit with the steam cycle and the compression train.

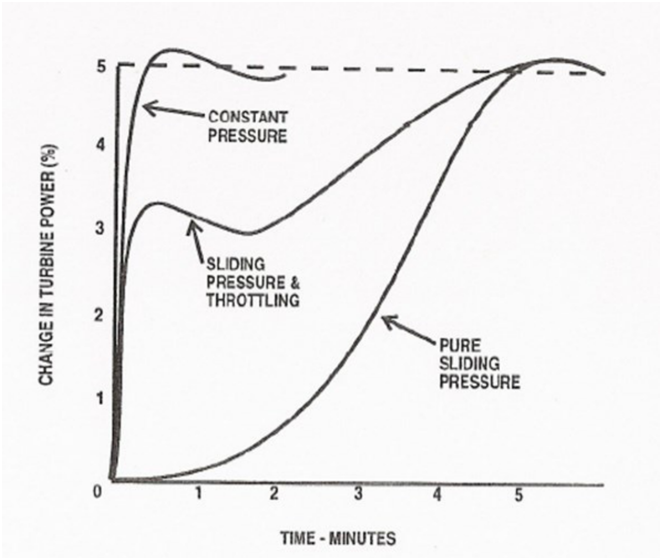


Figure 1: Change in power turbine response time for fixed and sliding pressure operation from Cotton, 1994 [18]

## 4. Evaluating the typical modes of part-load operation of a coal plant for operation with carbon capture, and associated ramp rates

When the boiler load of a coal plant reduces, pressures and mass flows in the steam cycle reduce to reduce the plant power output. There are several ways to control fossil plant at part-load.

- Fixed boiler pressure control: The steam pressure in the boiler is maintained and a valve at the HP turbine inlet is used to reduce the pressure along the turbine steam expansion path. Valve control induces significant losses in the valve and reductions of the turbine efficiencies, due to large changes of their pressure ratio, but provides fast dynamic response [18], compared to sliding pressure control, as illustrated in Figure 1.
- Sliding boiler pressure control: The boiler pressure in a once-through boiler (typically supercritical) is reduced by controlling the discharge pressure of the boiler feed pump. This method allows faster start-up procedures [19] and by eliminating the valve and maintaining the pressure ratio across the turbine ameliorates plant efficiency at part-load [18].

Partial-arc admission: A set of valves control the admission of steam to the turbine nozzles across the circumference or arc of the HP turbine rotor. Sequential closure of the control valves at part-load reduces the mass flow – hence the turbine power output – and lowers losses since only a fraction of the inlet mass flow is throttled. The ramp rate is typically controlled by the change in first-stage shell temperature of the HP turbine, which may results in slower rates compared fixed pressure and sliding pressure due to the gradient in thermal dilatation of parts of the first stage shell.

In practice, plants tend to use both boiler control philosophies [19] to trade-off between fast start-up, fast dynamic response at full load and part-load efficiency. Partial-arc admission is a turbine control philosophy, which can be combined with both boiler control methods [20, 21] to improve further part-load efficiency.

For carbon capture, steam turbines are operated at nominal load to meet the pressure requirements on the steam side of the reboiler. It is important to maintain the solvent reboiler temperature as high as possible during part-load operation to reduce solvent thermal energy of regeneration. Previous studies have indicated that solvent energy of regeneration is a strong function of reboiler temperature [22]. Lower temperature also results in lower pressure in the stripper and, by extension, the compression train, with an associated increase in compressor work required to reach the delivery pressure for $CO_2$.

This implies that sliding boiler pressure control and partial-arc admission may be preferred to fixed boiler pressure control at part-load since they maintain higher pressure ratios across the turbines, and by extension a higher IP turbine outlet pressure at part-load. With an increasing need for faster ramp rates, sliding boiler pressure control may be preferred to partial arc admission in the first stage of the HP turbine.

## 5. Methodology: an integrated steady-state part-load model to account for the impact of capture systems on steam turbines and $CO_2$ compressors

It is very likely that a capture unit will be expected to vent flue gas in case of emergency or during start-up or shutdown procedures [10, 23]. Power plants retrofitted with post-combustion capture also benefit from having a low pressure steam turbine, condenser and generator sized for the design flow before capture was fitted. Given that retrofitted plants are expected to make a significant contribution to decarbonisation of electricity generation, it can be expected that a large fraction of the fleet of CCS power plants will have the ability to by-pass capture. Since retrofitted units may be preferred for flexible operation, for the reasons indicated above, to new-build plants where additional investment for oversizing of the low pressure part of the steam cycle and condenser may be required, the focus of the modelling effort is directed here on a retrofitted plant that was built with carbon capture-ready features.

The modelling tool used for this work is the process simulation software ASPEN Plus©.

Power plant

The plant is based on an Advanced Super-Critical (ASC) Boiler and Turbine designed for a gross power output of about 625 MWe without capture. The steam cycle is a triple pressure cycle with re-heat. It includes capture-ready steam turbines with the IP turbine outlet pressure matching the pressure required for solvent thermal energy of regeneration [24]. The live steam parameters are 298 bar and 600ºC and the re-heated steam conditions are 64.5 bar and 367ºC. The steam turbine plant consists of HP turbine, IP turbine and LP turbine with steam bleeds for regenerative heating of feed water and condensate. There are seven feed water heaters that produce boiler feed-water at 309.6ºC.

Steam extraction and integration of the capture unit with the power cycle

Process steam for solvent regeneration is extracted from the IP/LP crossover pipe with a nominal design pressure without $CO_2$ capture of 4 bar. When the plant is retrofitted, this pressure is maintained with a pressure control valve at the inlet of the LP turbine. Changes in crossover pressure/IP outlet pressure and the amount of throttling occurring in the LP turbine inlet valve depends on the load of the plant and the amount of steam extracted. The pressures throughout the cycle are estimated by using the Stodola's Ellipse Law [25].

The philosophy of steam extraction is crucial in the operation of the power plant with integrated capture and it needs to comply with the following targets:

- Safety in operation: it should impose no hazard to the power plant hardware or the capture plant hardware or solvent.
- Flexibility: It needs to accommodate variable steam load and variable steam conditions (pressure and temperature)
- Efficiency: It should be designed to minimize the impact on power generation efficiency.

In this configuration, the pressure control valve is designed to maintain the crossover pressure at 4 bara full load operation with carbon capture. The amount of steam extracted at this point is optimized by varying solvent flow rate to maximize total power output, and reduce the electricity output penalty to a minimum at 90% capture

Steam is desuperheated prior to the solvent reboiler by passing through two indirect contact de-superheaters of the tube bundle type. The pressure drop of the steam extraction line is mainly due to the de-superheaters. Experience based rules of thumb suggest a pressure drop between 0.2 to 0.68 bar per heat exchanger [26-29]. The pressure drop in the extraction line is assumed to be 1 bar to account for the pressure drops in the de-superheaters and to reflect the fact that the unit is a retrofitted unit with higher pressure drops associated with an increased length of the pipework to the reboiler. This pressure drop is corrected at part load operation as explained in the modelling section.

Capture plant description

The capture plant is a standard absorption – desorption process, in which a solution of monoethanolamine (MEA) by 30%wt is used to capture 90% of the $CO_2$ present in the given flue gas stream. The plant is designed to process 526 kg/s of flue gas containing 13.4 mol% $CO_2$ divided into two identical trains. The flue-gas is fed to the absorber, where it is brought in contact with the solvent, which flows downwards over a packed bed with Mellapax 250Y. Lean solvent is cooled to 40°C prior to the absorber. The reboiler receives saturated process steam at 3 bar (133.6ºC) in order to achieve a solvent regeneration of 120ºC at full load operation The condensate is returned into the boiler feed water train after being used to de-superheat the steam extracted from the crossover.

Compression train

The $CO_2$ stream compression system consists of three trains of a 7 stage integrally geared centrifugal turbocompressor. Intercooling after the 2nd, 4th and 6th stage is used to achieve low power consumption for the compressor drive. The Peng-Robinson equation of state is used to predict the thermodynamic properties of the mixture with consists of mainly $CO_2$ and some water. Performance maps in ASPEN, validated against performance data of large scale $CO_2$ compressors, are used to represent the operating envelope, including variations in rotational speed of the shaft and part-load efficiencies.

Part-load modelling

A fully integrated model of the described power and capture plants has been developed in Aspen Plus® with the capability of predicting part –load behavior. For this purpose a set of turn-down boiler data with detailed conditions of steam parameters, fuel and air input and feed water conditions from a comprehensive industry-led study [30] are used to estimate the steam conditions and corresponding fuel use at part-load operation and predict the flue gas flow and composition to be treated in the capture plant at any load. The boiler turn-down strategy is based on sliding pressure and it can turn-down from 100% to 40% Maximum Continuous Rating (MCR) without any additional fuel. The discharge conditions of the steam turbines are estimated using the Stodola's Ellipse Law assuming constant isentropic efficiencies taken from European Benchmarking Task Force Common Framework [31].

The pressure drop in the boiler and re-heater is also estimated from the boiler data set and fitted to a correlation based on $\rho \cdot V^2$ pressure loss. This correlation is also used to predict the pressure loss in the pipework and the de-superheaters of the steam extraction line at lower steam loads than the design operating point.

The feed water heaters are designed with a 3ºC LMTD and the estimated area is kept constant to predict part-load operation. The overall heat transfer coefficient of all heat exchangers is corrected at part-load based on a power load correlation on both hot and cold side.

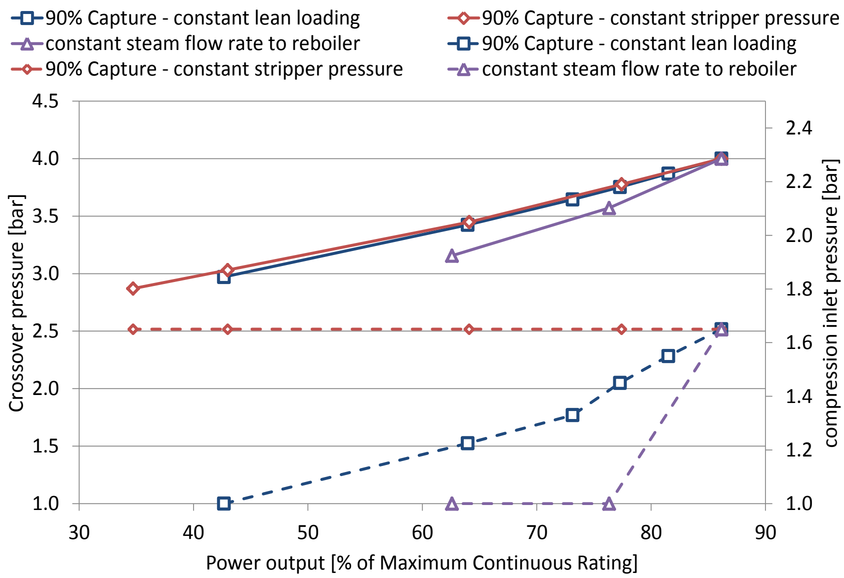


Figure 2a

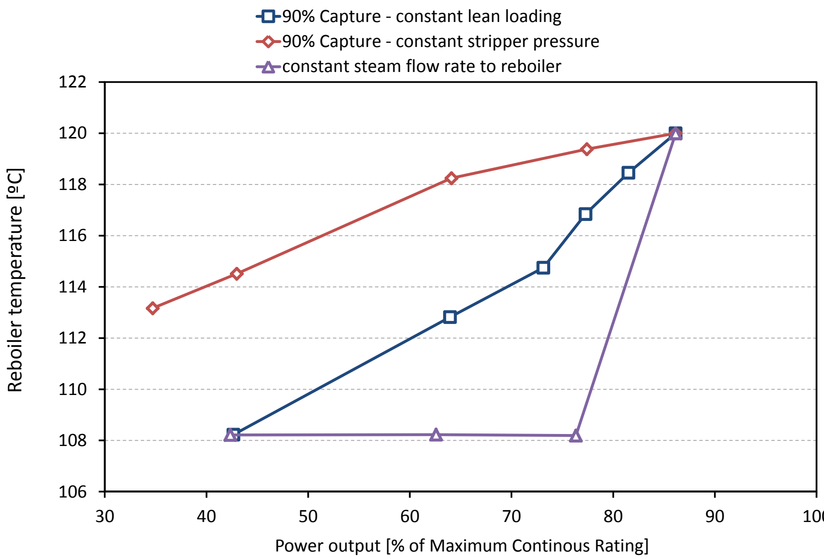


Figure 2b

Figure 2: Variation at part-load of process parameters of the capture unit at the interface with the power cycle and the compression train. IP/LP crossover pressure of the steam cycle and compression inlet pressure are shown in Figure 2a, the reboiler temperature in Figure 2b

With respect to the capture plant, the absorption of $CO_2$ is modelled with the Aspen Plus rate-based approach where actual rates of mass and heat transfer as well as chemical reactions are considered. The mass transfer is described using the two-film theory based on the rigorous Maxwell-Stefan theory. The ENRTL model is used to estimate actual activity and deviations from ideal behavior due to electrolyte forces. The gas phase is treated as an ideal gas. During part load operation, the mass transfer in the absorber column is estimated rigorously based on the kinetic and equilibrium reactions described above and the mass transfer correlations implemented in Aspen Plus to estimate mass transfer coefficients in structured packing. The performance of the heat exchangers of the capture plant (reboiler, Lean Rich heat exchangerand de-superheater) is estimated in the same way as the feed water heaters.

## 6. Performance at part-load

In a comprehensive study carried out for IEAGHG by Foster Wheeler [32], the authors point out that specific aspects of flexible operation have yet to be investigated, notably around the interface between the capture unit and the power cycle. They indicate that “a relatively narrow band of temperatures of the steam used for solvent regeneration is acceptable, without affecting the characteristics and properties of the solvent” and also conclude that boiler sliding pressure control may be the method of choice.

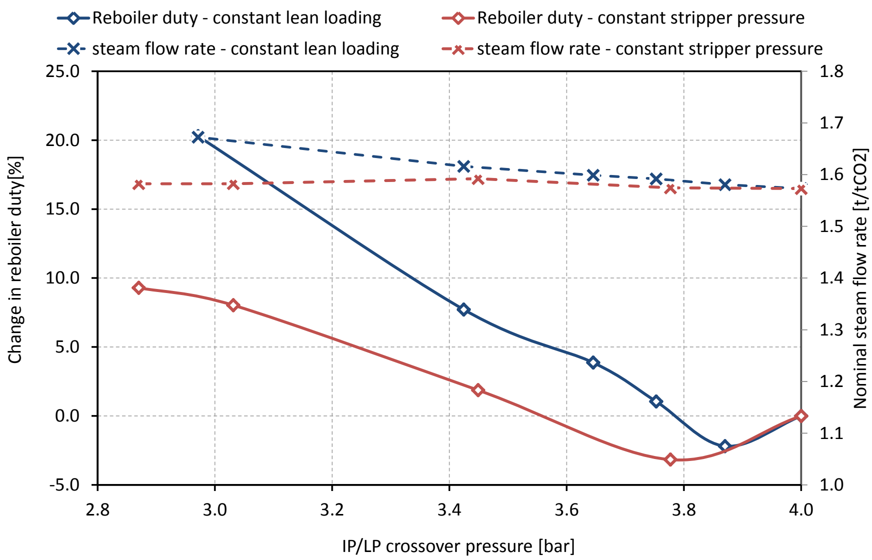


Figure 3: Relative variations in reboiler duty and absolute variation in steam flow rate for solvent regeneration as a function of changes in IP/LP crossover pressure caused by a reduction of fuel input to the boiler

We compare two part-load operating strategies for efficient operation of the CCS power plant for a range of load, reported as the proportion of maximum continuous rating of the plant and examine the interface process parameters (reboiler temperature, reboiler steam pressure and compression inlet pressure) of the capture unit. These are:

Constant lean solvent loading (blue line in Figure 2, Figure 3, Figure 4 and Figure 5)

As steam extraction pressure varies with the boiler and the steam cycle load, the reboiler duty and the solvent flow rate are adjusted to maintain a constant solvent lean loading.

Constant stripper pressure (red line in Figure 2, Figure 3, Figure 4 and Figure 5) As steam extraction pressure varies with the boiler and the steam cycle load, the reboiler duty and the solvent flow rate are optimisied to maintain a constant pressure at the compression inlet.

Since the plant has the ability to by-pass it can reach 100% MCR by venting flue gas, and operates at circa 86% MCR with 90% capture and 100% of the maximum fuel input to the boiler. The optimisation of process parameters is carried out with the objective to maximise the total power output and takes into account variations in compression power with changes in stripper pressure and variations in the steam cycle power output with changes in reboiler temperature and reboiler duty.

At part-load with a reduced fuel input to the boiler, the pressure of the working fluid in the boiler decreases to reduce the power output of the steam cycle. The IP/LP crossover pressure reduces along with the operating pressures of the steam turbines. Lower pressure drop in the steam extraction line for solvent regeneration compensates to a certain extent and a reduction in the approach temperature in the reboiler partially mitigates the effect of a drop in crossover pressure, but effectively steam condenses at a lower temperature in the reboiler, as illustrated in Figure 2a and Figure 2b.

Solvent energy of regeneration is directly impacted by changes in reboiler temperature caused by a reduction in the crossover pressure (and effectively fuel input to the boiler). This is illustrated in Figure 3 for a range of crossover pressures corresponding to variation of maximum fuel input from 100% to 40% (86% MCR to 42% MCR). Although the nominal steam flow rate (in tonne of steam per tonne of $CO_2$) is relatively constant, the latent energy of steam/water varies with pressure. An increase in reboiler is observed at 42% MCR of, respectively, 20% for the control strategy with constant lean loading and 10% for the control strategy with constant stripper pressure, relative to the reboiler duty, in GJ thermal per tonne of $CO_2$, when the plant is operated at maximum fuel input and 90% capture.

By maintaining the stripper pressure at part-load, an improvement is observed in the electricity output penalty compared to the control strategy maintaining a constant solvent lean loading, shown in Figure 4b. This is attributed to two factors. The higher reboiler temperature effectively limits steam extraction level from the turbines and the higher compression inlet reduces the compression power. In return, there is an increase in the power required for the solvent circulating pumps. For plants operated extensively at part-load this could be significant. With a fuel input reduced to 50%, corresponding to 42% of maximum continuous rating, the difference in the electricity output penalty is around 30 kWh/t$CO_2$. For comparison the electricity output penalty at 86% of MCR, 100% fuel input and 90% capture is 361 kWh/t$CO_2$.

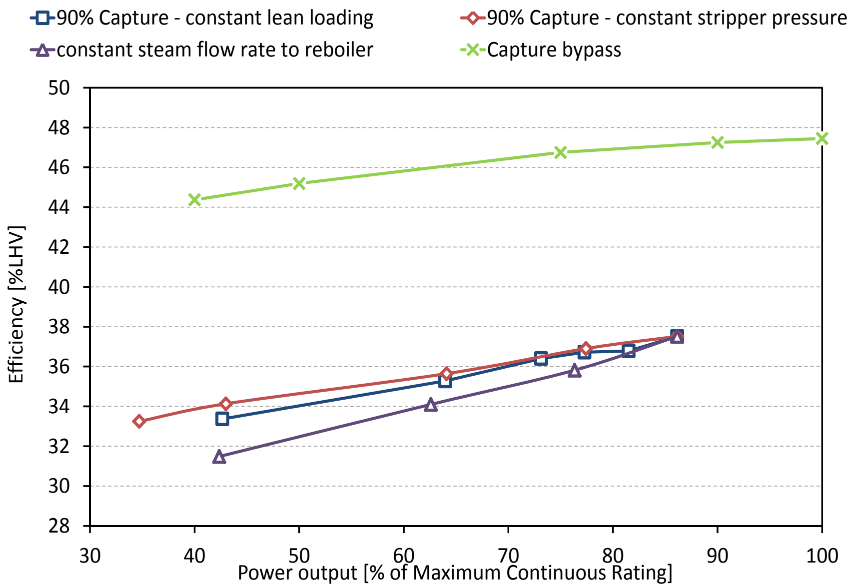


Figure 4a

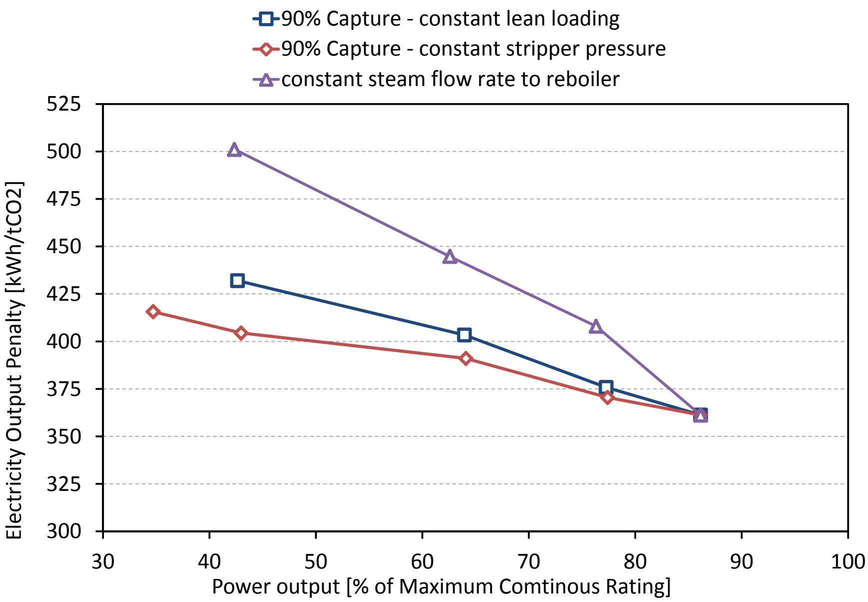


Figure 4b

Figure 4: Variations in plant thermal efficiency in Figure 4a and electricity output penalty in Figure 4b at part-load for a capture-ready coal plant retrofitted with capture

## 7. Flexible operation and ramp rates

Pulverised coal plants without capture are currently operated with both fixed boiler pressure and sliding boiler pressure, depending on the load range. Fixed boiler pressure tends to be used between 90% and 100% for frequency control and sliding pressure between 50 and 90% of MCR. Typical ramp rates for the various control philosophy used for state-of-the-art coal power plants without carbon capture are provided in Table 1.

With carbon capture, it is important to understand where the bottlenecks for ramping up and down the plant output stand. Figure 4a shows the variations in the plant thermal efficiency for two part-load strategies, and for operating with capture by-pass to return the plant to its maximum output with all ancillary power consumption shut down. It is currently expected that $CO_2$ compressor flexibility would not be the limiting factor to flexible CCS.

IEAGHG [30] indicates that $CO_2$ compressors do not add specific constraints to a flexible CCS power plant capability to change load and that ramp rates of “in-line” and “integrally-gear” centrifugal compressors are in the order of seconds. Likewise, rapid variations in the output of the low pressure turbine can be expected by operating the valves in the steam extraction line to the reboiler and the inlet of the turbine. Temperature gradients are relatively small over a wide range of steam extraction rate, which indicates that thermal dilatation differences between the casing and the rotor may be acceptable. It is thus possible to vary steam extraction rates rapidly to modulate the generator output. The limiting factors to flexible operation are, therefore, likely to be associated with parts of the process within the boundaries of the capture unit. $CO_2$ flows from the capture plant to the compression train are likely to continue for a period of time significantly longer than the typical shut-down procedure of compressors, due to the thermal inertia in the capture plant reboiler and stripper sump. Van Der Wijk et al. [10] report ramp rates for flexible CCS plants of the order of 1%/min compared to 3-5%/min.

Table 1: typical ramp rates of supercritical coal power plants (without carbon capture)

| Load range (% MCR) | Control philosophy | Ramp rates (% MCR/min) [22] | Gradient of change in crossover pressure (bar/% MCR) |
|---|---|---|---|
| 30-50 | Fixed boiler pressure | 2-3 | High |
| 50-90 | Sliding boiler pressure | 4-8 | Low |
| 90-100 | Fixed boiler pressure | 3-5 | High |

In practice, diverting the steam flow rate from the reboiler to the LP turbine would only take of the order of hundreds of seconds. Venting rapidly a large fraction of the $CO_2$ inventory in the compression is also possible, although an operator may choose not to, over a certain $CO_2$ price (or possibly for health and safety reasons). If these ramp rates were added to those of the boiler/steam cycle, the overall ramp rate of the plant would be significantly improved. Table 2 shows some estimated values for ramp up scenarios.

Ramp down rates can also be improved by rapidly increasing steam extraction to the reboiler for increased capture levels, reducing lean solvent loading for time-varying solvent regeneration or additional solvent regeneration. The ramp rate down of a flexible CCS power plant output is then likely to be the sum of the ramp rate of the boiler at decreasing fuel input and the ramp rate up for the compressors (assuming it is slower than that of the turbine).

Table 2: Estimates of achievable ramp rates with capture by-pass and/or solvent storage with delayed regeneration

| Control philosophy to ramp up plant output | Fraction of output at any given load | Estimated additional ramp to boiler/steam cycle ramp rate | Limiting factor |
|---|---|---|---|
| Steam diversion to LP turbine | 16-20% | 4-5%/min | Steam valve closure/opening |
| $CO_2$ compressor rapid shutdown and $CO_2$ venting | 7-11% | 2-3%/min | Compressor |
| $CO_2$ compressor shutdown w/o $CO_2$ venting | 7-11% | <0.1%/min | Thermal inertia in capture plant solvent sump |

## 8. Additional solvent regeneration to manage compressed $CO_2$ flows

Managing $CO_2$ flows in integrated CCS networks may become valuable as the deployment of the technology moves from single source to single sink projects to networks of $CO_2$ pipelines and injection sites. In electricity systems with large amount of wind and solar, it is likely that a large fraction of the fleet of existing fossil power stations with CCS would be requested to reduce or increase their electricity output over the same period of time, with obvious implications for $CO_2$ networks. We examine the $CO_2$ flow pattern of a flexible CCS power plant operating with additional solvent regeneration, after an event of rich solvent storage. The limiting factors to additional solvent regeneration are, in this case, the steam flow rate sent to the reboiler of the capture unit and the inlet pressure of the compression train.

At part-load with a reduced fuel input and with a steam flow rate equivalent to 100% fuel input 90% capture, it is possible to maintain the $CO_2$ flow to the pipeline within 90% of its design flow down to 62% of maximum continuous rating. This is illustrated in Figure 5 where the $CO_2$ flow of a plant actively operated to maximize its compressed $CO_2$ flow is compared to the compressed $CO_2$ flow of a plant operated at part-load with 90% capture. Plant efficiency and electricity output penalty are also reported in Figure 4a and Figure 4b (purple line) and the key process parameter at the interface between the capture unit, the power cycle and the compression in Figure 2a and 2b (purple line).

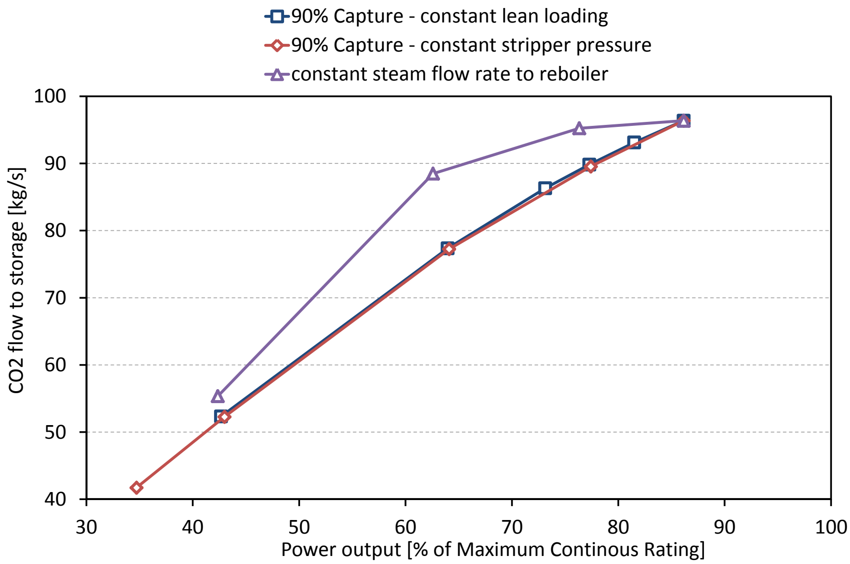


Figure 5: Compressed $CO_2$ flow rates to pipeline/storage at part-load.
The line of constant steam flow rate to reboiler (purple) illustrates a flexible CCS power plant regenerating additional solvent after an event of rich solvent storage

## 9. Conclusions

Enhancing the operating flexibility and the performance of CCS power plants is necessary for the operation of resilient CCS systems where intermittent low-marginal cost generation (e.g. wind or solar) may shift fossil power plants from base-load to mid-merit plants.

A novel part-load strategy is proposed for pulverised coal plants with post-combustion capture, building on insights from an integrated model of a steam cycle, a post-combustion capture unit and a compression train in ASPEN Plus. Maintaining the stripper pressure by adjusting the solvent flow rate when the fuel input to the boiler is reduced improves performance compared to part-load strategies at constant lean loading.

We show that the ramp rate of the boiler/steam cycle of a flexible CCS power plant can be enhanced by rapidly diverting steam from the capture unit to the steam cycle and by ramping simultaneously the compression train. This is an important feature for electricity systems where revenues from providing anciallary services to the grid are important, e.g. in scenarios with large amount of wind generation [10].

Since variations in $CO_2$ flows in transport networks follow the electricity output of CCS power plants, we also examine briefly the ability and the limitations of flexible CCS power plants to decouple electricity output from compressed $CO_2$ production to smooth variations in pipeline flows. The initial analysis shows that 90% of the design flow can be maintained over a wide range of loads by delaying solvent regeneration, after an event of rich solvent storage.

## Acknowledgements

The authors would like to acknowledge funding from the UK CCS Research Centre for the FleCCSnet project (UKCCSRC-C1-40). Mathieu Lucquiaud is funded by a UK Royal Academy of Engineering Research Fellowship.

## References

[1] Chalmers, H., Gibbins, J., Initial evaluation of the impact of post-combustion capture of carbon dioxide on supercritical pulverised coal power plant part load performance. Fuel, 2007, 86, 2109–2123

[2] Chalmers, H., Lucquiaud, M., Gibbins, J., Leach, M., 2009. Flexible Operation of Coal Fired Power Plants with Post combustion Capture of Carbon Dioxide., J. Environ. Eng, 2009, 135, 449–459.

[3] Cohen, S., Rochelle, G.T., Webber, M.E., 2011. Optimal operation of flexible post-combustion CO2capture in response to volatile electricity prices. Energy Proc.4, 2604–2611.

[4] Cohen, S., Rochelle, G.T., Webber, M.E., 2013. Optimal CO2capture operation in anadvanced electric grid, Energy Procedia Volume 37, 2013, 2585–2594.

[5] Delarue, E., Martens, P., D'haeseleer, W., 2012. Market opportunities for powerplants with post-combustion carbon capture. Int. J. Greenh. Gas Control, 6, 12–20.

[6] Oates, L., Versteeg, P., Hittinger, E., Jaramillo, P. Profitability of CCS with flue gas bypass and solvent storage. Int. J. Greenh. Gas Control,, 27, 2014, 279–288

[7] Haines, M.R., Davison, J., 2009. Designing carbon capture power plants to assist inmeeting peak power demand. Energy Proc. 1, 1457–1464.

[8] Brasington, R.D., Integration and Operation of Post-Combustion Capture System on Coal-Fired Power Generation: Load Following and Peak Power. 2012, MSc Thesis, Massachusetts Institute of Technology, MA, USA.

[9] Pati˜no-Echeverri, D., Hoppock, D.C., Reducing the energy penalty costs ofpostcombustion CCS systems with amine-storage. Environ. Sci. Technol., 2012. 46, 1243–1252.

[10] Van der Wijk, P.C., Sjoerd Brouwer, A., Van den Broek, M., Slot, T., Stienstra, G., Van der Veen, W., Faaij, A.P.C. Benefits of coal-fired power generation with flexible CCS in a future northwest European power system with large scale wind power. International Journal of Greenhouse Gas Control , 2014, 28, 216–233

[11] Ziaii, S. Rochelle, G.T., Edgar, T.F. Optimum design and control of amine scrubbing in response to electricity and CO2 prices, Energy Procedia, 2011, 4, 1683-1690

[12] Ziaii, S. Dynamic Modeling, Optimization, and Control of Monoethanolamine Scrubbing for CO2 Capture, 2012, PhD Thesis, University of Texas at Austin, TX, USA

[13] Gibbins, J.R., Crane, R.I. Scope for reductions in the cost of CO2 capture using flue gas scrubbing with amine solvents. Proc. Instn Mech. Engrs, 2004, Vol. 218 Part A: J. Power and Energy

[14] Mac Dowell, N., N.J. Samsatli, and N. Shah, Dynamic modelling and analysis of an amine-based post-combustion CO2 capture absorption column. Int. J. GHG Con., 2013. 12(247-258).

[15] Mac Dowell, N. and N. Shah, Identification of the cost-optimal degree of CO2 capture: An optimisation study using dynamic process models. Int. J. GHG Con., 2013. 13: p. 44-58

[16] Mac Dowell and Shah, Computers and Chemical Engineering, 2014, Under Review

[17] Mac Dowell and Shah, Flexible operation of a super-critical coal-fired power plant integrated with a post-combustion CO2 capture process, 2014, Energy Procedia, this conference

[18] Cotton, K. Evaluating and improving steam turbine performance, 1994. 2nd edition, Rexford, New York, Cotton Fact

[19] Vitalis, B. Constant and sliding-pressure options for new supercritical plants, 2006, Power, January-February 2006

[20] Vitalis, B., Hunt, P., Constant and Sliding Pressure Options for New Supercritical Plants, Power-Gen International 2005, 6-8 December 2005, Las Vegas, Nevada, USA

[21] Silvestri, G. Method for heat rate improvement in partial-arc steam turbine, 1989, United States Patent, Patent Number: 4,888,954

[22] Abu-Zahra, M.R., et al., CO2 capture from power plants: Part I. A parametric study of the technical performance based on monoethanolamine. 2007. International Journal of Greenhouse Gas Control 1 (1), 37–46

[23] E.ON, Kingsnorth Carbon Dioxide Capture and Storage Demonstration Project FEED Study. 2011

[24] Lucquiaud, M., Gibbins, J. Retrofitting CO2 capture ready fossil plants with post-combustion capture. Part 1: requirements for supercritical pulverized coal plants using solvent-based flue gas scrubbing. 2009. Proc. IMechE Part A: J. Power and Energy, Vol. 223 , 213-226

[25] Stodola, A. Steam and Gas Turbines, 1927, New York, NY, USA, McGraw- Hill

[26] Walas S. M., Chemical Process Equipment: Selection and Design, Butterworths, Stoneham, MA 1988.

[27] Turton R., et al, Analysis, Synthesis, and Design of Chemical Processes, Prentice Hall, Upper Saddle River, NJ 1998

[28] Branan, C., Rules of Thumb for Chemical Engineers, Gulf Publishing, Houston, TX 1998

[29] Haslego, C., "The Chemical Engineers' Resource Page", www.cheresources.com, Richmond, VA 2000

[30] Panesar, R., Lord, M., Simpson, S., White, V., Gibbins, J., Reddy, S. (2009) Coal-Fired Advanced Supercritical Retrofit with CO2 Capture, UK Department of Energy and Climate Change, Contract No.: C/08/00393/00/00, June 2009

[31] Sanchez Fernandez E. et al. Thermodynamic assessment of amine based CO2 capture technologies in power plants based on European Benchmarking Task Force methodology performance of Power plants with CO2 capture based on EBTF. Fuel (129),2014, pp 318-329

[32] IEAGHG, Operating Flexibility of Power Plants with CCS, 2012, Report 2012/06